Conversion Efficiency of Laser-produced Plasmas at 13.5 nm and Colliding Plasmas as EUV Sour**ces**

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International Workshop on EUV and Soft X-Ray Sources (2016 Source Workshop) , Amsterdam, November 8th 2016

Outline

- Properties of Laser Produced Plasmas
- Measured and Calculated Conversion Efficiencies
- Colliding Plasmas

Laser produced plasmas (LPPs)

Expansion velocity ≈ 10^6 - 10^7 cms^{-1}

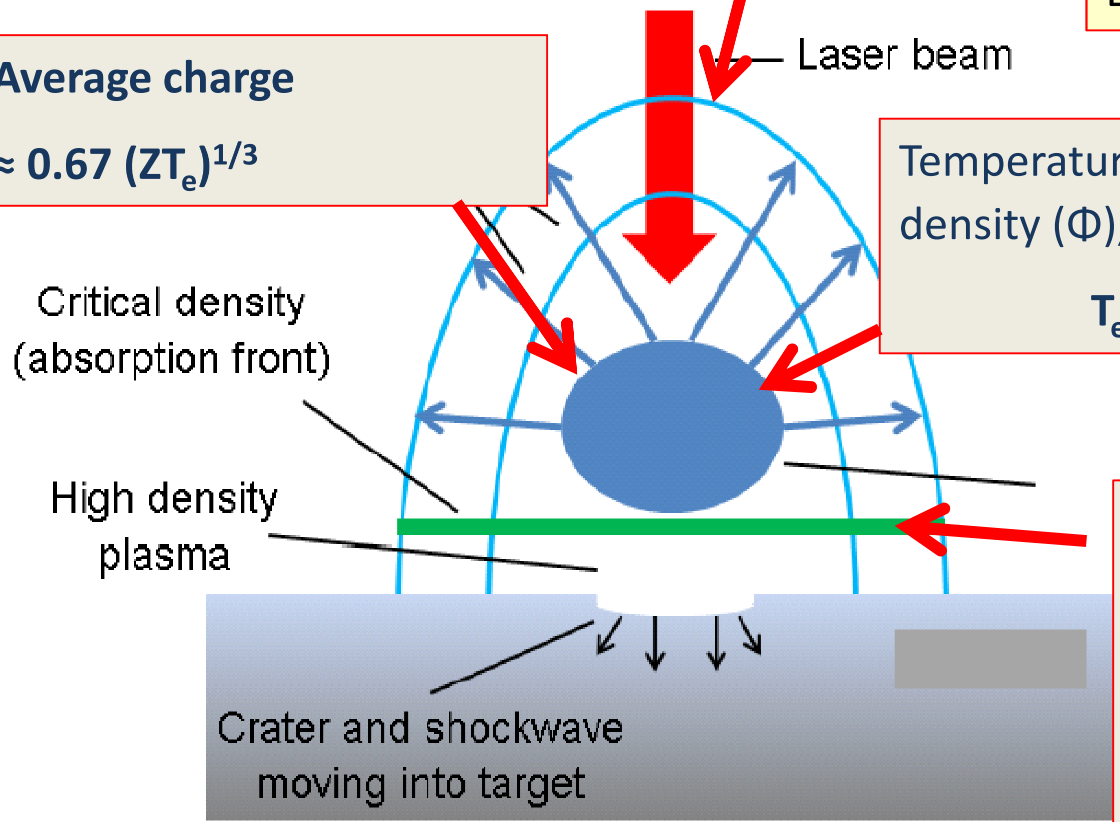
For ns duration plasmas Collisional Radiative (CR) Equilibrium assumed

Average charge

≈ 0.67 $(ZT_e)^{1/3}$

Temperature depends on laser power density (Φ),

T_e(eV) α $(\lambda^2\Phi)^{3/5}$ …CR model



Critical electron density,

n_{ec} $=10^{19} – 10^{21}$ cm^{-3}

depends on laser wavelength

(n_{ec}~[$10^{21}/\lambda(\mu m)^2$] cm^{-3})

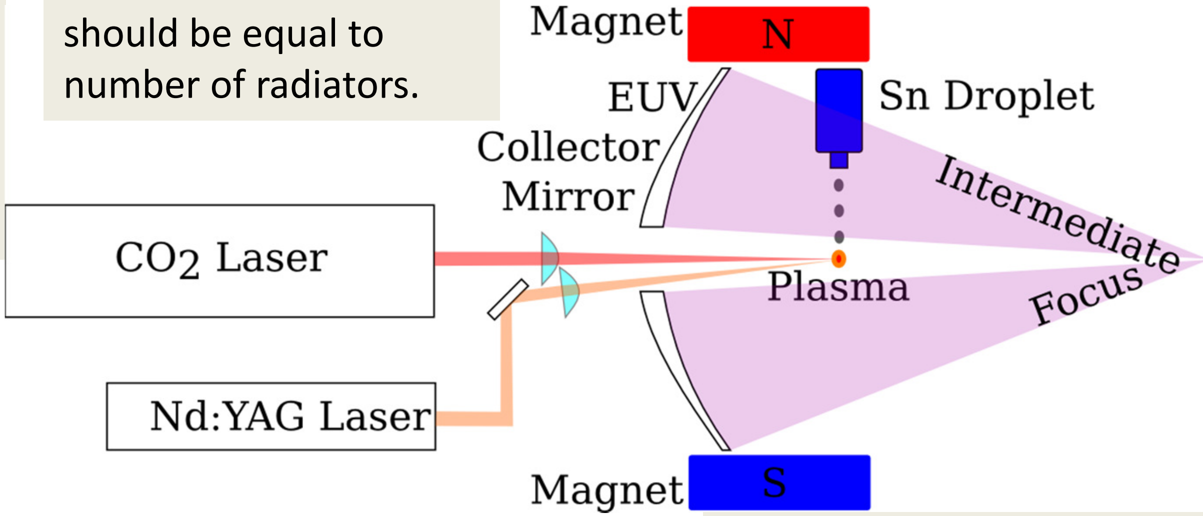
To conserve momentum, plasma expands perpendicular to target surface

Target Geometry for HVM

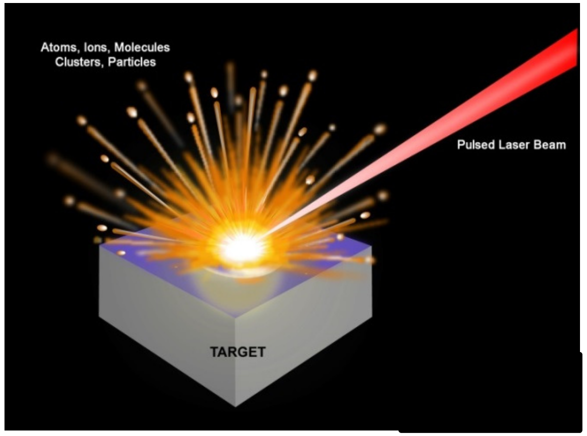
At high repetition rates, it is not possible to use solid (slab) targets.

For EUV, rep. rate $=10^5$ Hz

Low mass Sn content. number of Sn atoms should be equal to number of radiators.



To minimise debris, target should be fully ionized by end of laser pulse.



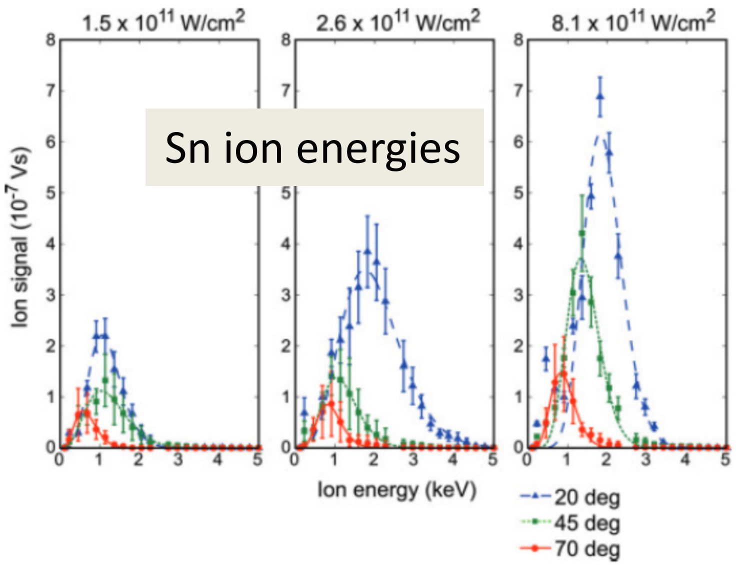
- Gigaphoton and CYMER have obtained > 200 W at Intermediate focus. Maximum CE ~ 5%.
- Gigaphoton: Nd:YAG prepulse, CO_2 main pulse, Cymer: CO_2 main and pre-pulses.

Energy Losses

Plasma expansion:

Fastest and most highly charged ions at centre of the plume.

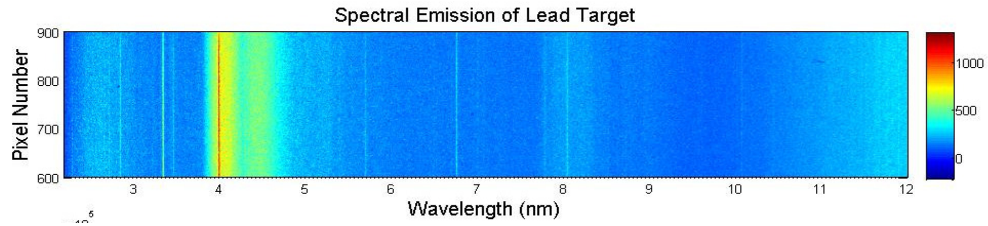
(O'Connor et al. 2011, JAP 109,, 073301)



Expansion velocity increases with Φ.

Reduce by reducing Φ or by reducing shock wave momentum (target density)

Radiation:



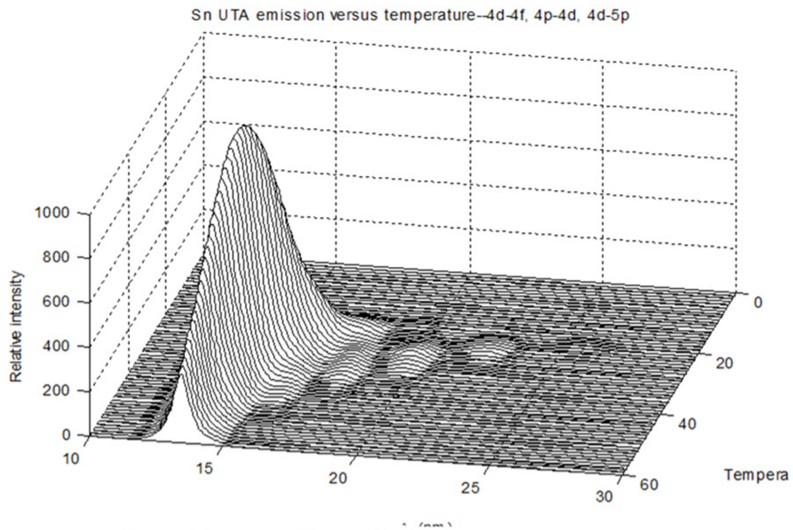
Spectrum consists of:

- lines (bound-bound transitions), in some cases lines cluster together to form a UTA (unresolved transition array)
- recombination radiation (bound-free transitions): $I \propto n_e^2 \langle z \rangle^4$ where $\langle z \rangle$ is the average ionic charge
- bremsstrahlung (free-free): $I \propto n_e^2$,

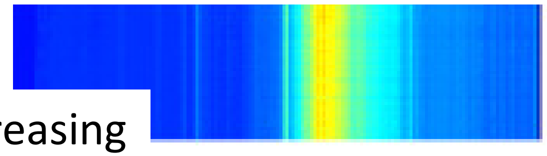
Maximise line emission by reducing opacity,
Maximise spectral purity by reducing recombination

Density has a 'sweet spot'

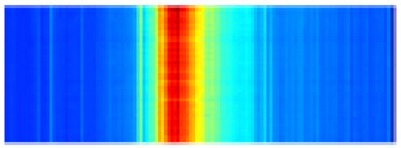
Sn UTA emission

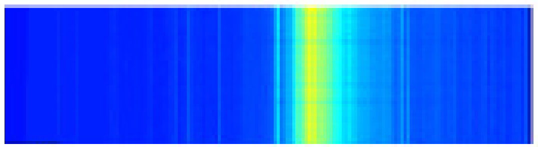


$4p^6 4d^N$- $4p^6 4d^{N-1} 4f$
emission in Sn @13.5 nm



Increasing power density ↓



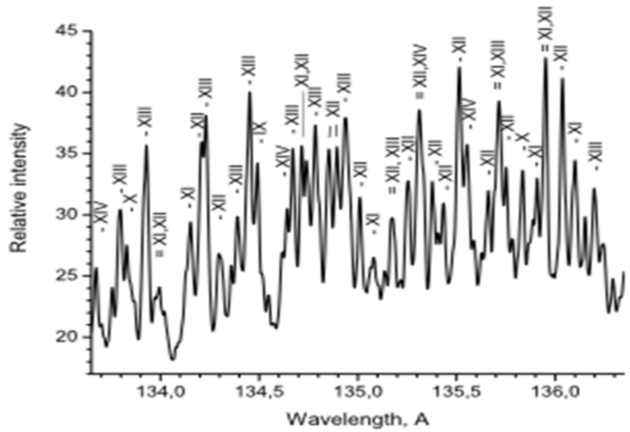


Lines due to SnXI –Sn XIV

Churilov and Ryabtsev, 2006,Phys. Scr. 73 614-619

More recent study has shown the need to revisit and refine analysis

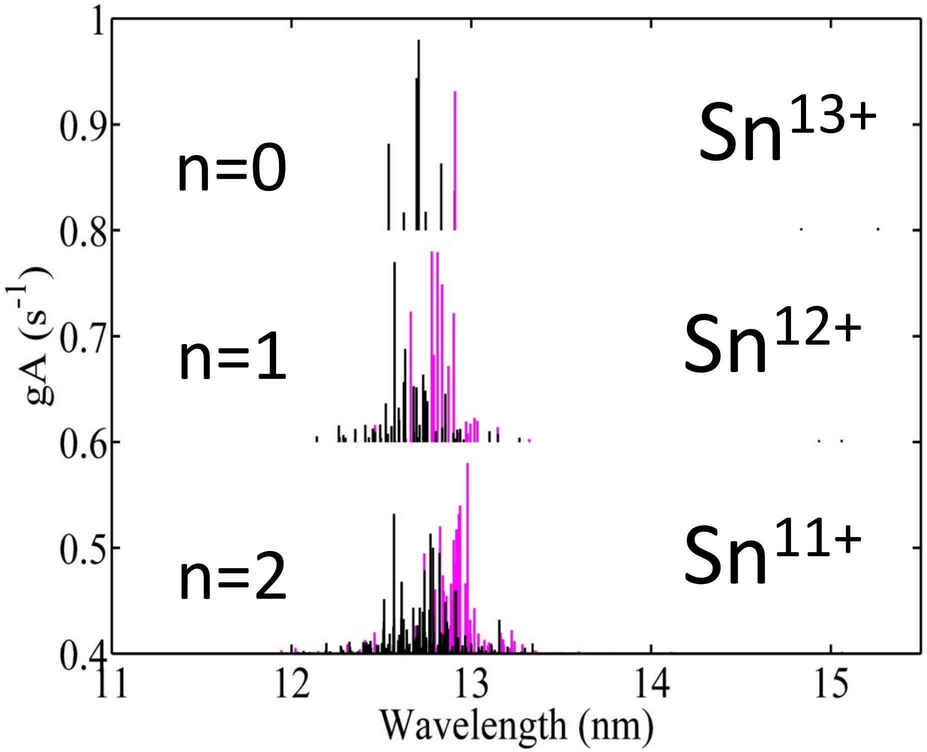
Windberger et al. 2016, PRA 94, 012506



Spectral shape modified by density effects: opacity, satellite lines

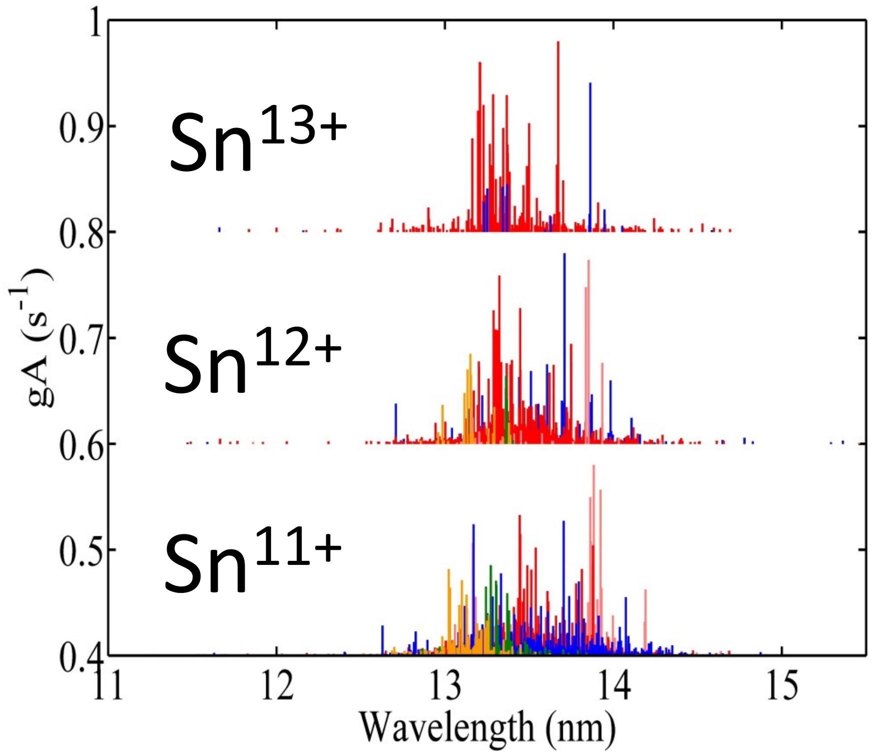
Sasaki et al. 2004. IEEE Journal of Quant. Electron.10, 1307

Sn resonance and satellite lines



$4p^64d^{n+1} – 4p^64d^n4f$

$4p^64d^{n+1} – 4p^54d^{n+2}$



$4p^64d^n5s – 4p^64d^{n-1}5s4f$

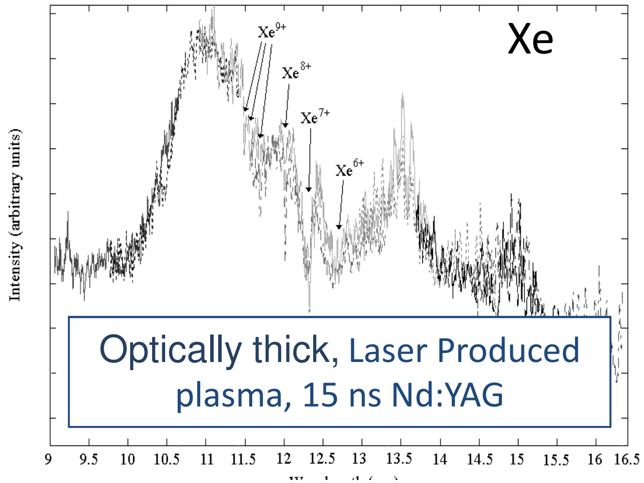
$4p^64d^n5s – 4p^54d^{n+1}5s$

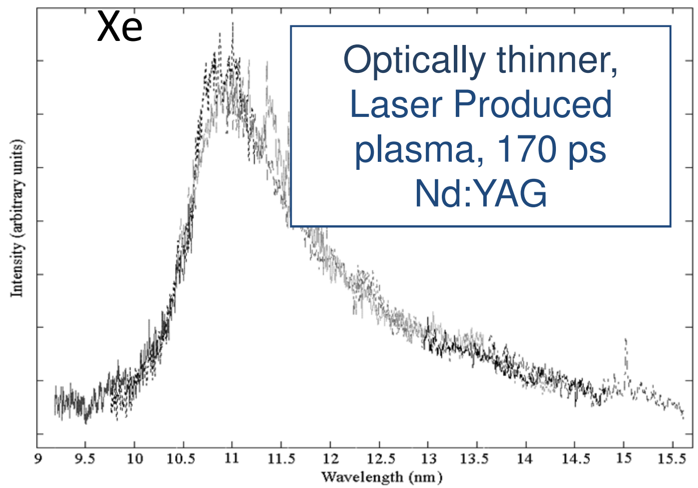
$4p^54d^{n+2} – 4p^54d^{n+1}4f$

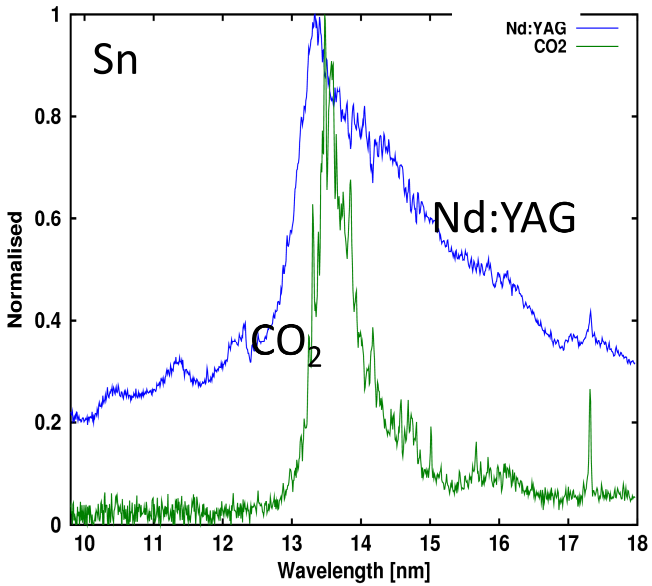
$4p^64d^n4f – 4p^54d^{n+1}4f$

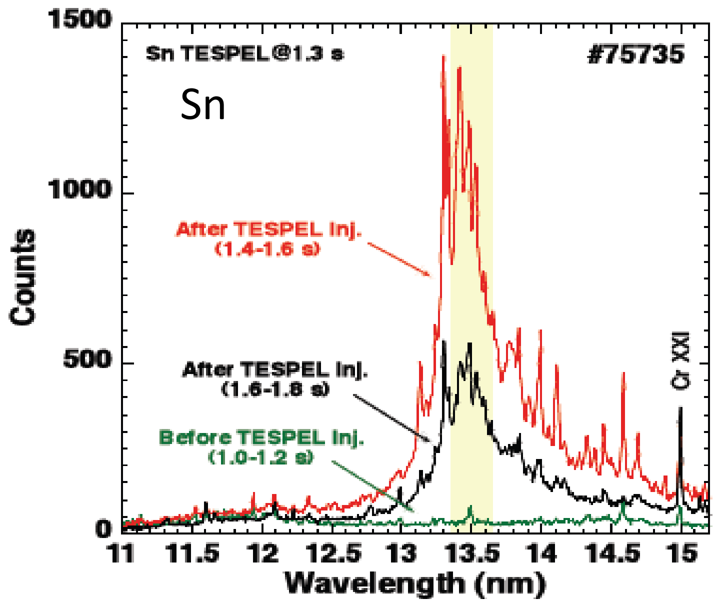
$4p^64d^n4f – 4p^64d^{n-1}4f^2$

Optical thickness depends on pulse duration, laser wavelength and target purity/density









ns-LPPs optically thicker than ps -LPPs

Nd:YAG LPPs optically thicker than CO_2 LPPs

Reducing target density reduces opacity.
NIFS spectra

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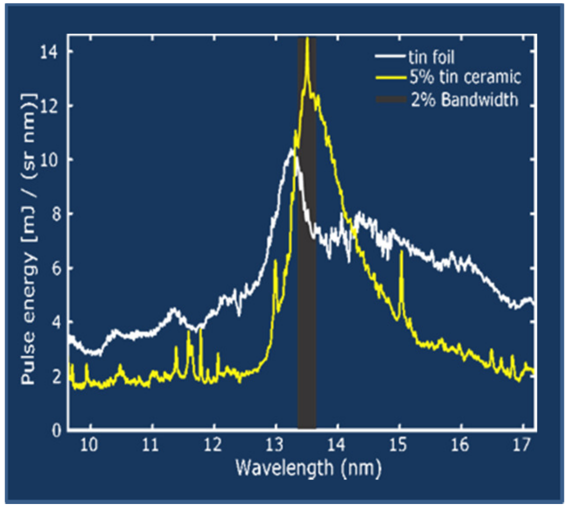
In–Band Conversion Efficiency (CE)

Slab Targets:

<u>Nd:YAG plasmas: 2%<CE<3%</u>

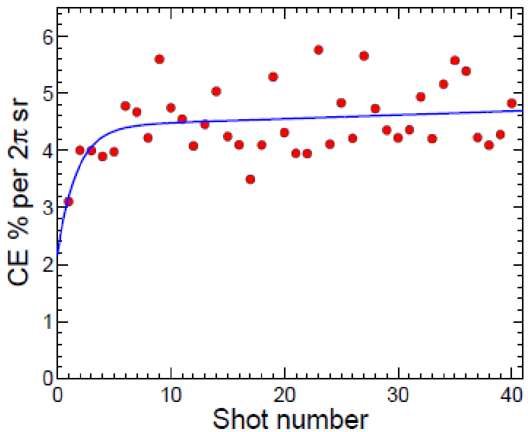
e.g. CE~2.3% /2π sr for 100% Sn @Φ= $1.6x10^{11}Wcm^{-2}$
CE~2.9% /2π sr for 5% Sn @Φ= $2x10^{11}Wcm^{-2}$
(Hayden et al. 2006 , JAP 99, 9)



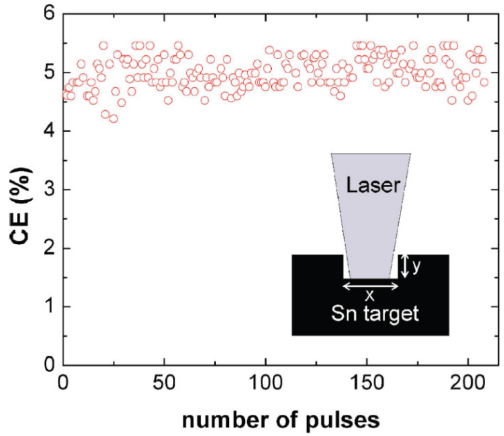
<u>CO_2 plasmas: 2%<CE<3%</u>

CE ~ 2.6% for 100% Sn @Φ= $1.6x10^{11}Wcm^{-2}$
(Tao et al. 2008, APL 92, 251501)

CE increased after multiple shots on same target position to ~4.5%.
Lateral expansion reduced.

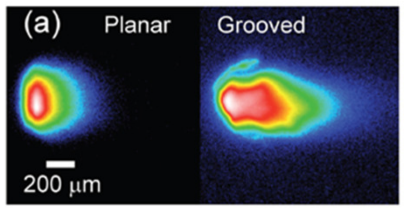


Grooved Targets:



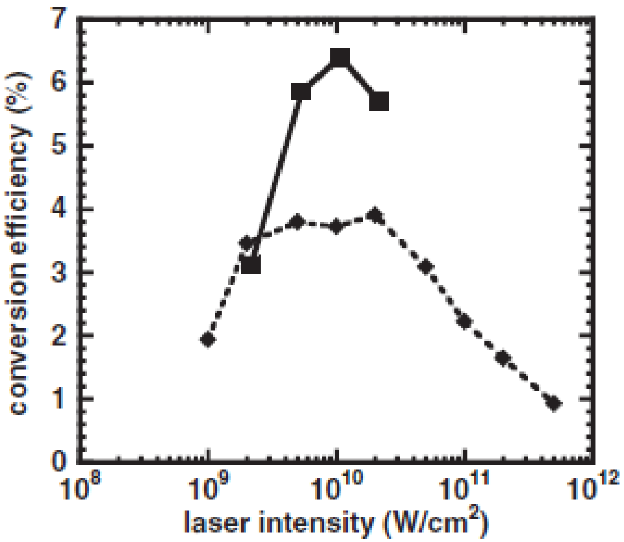
CO_2 pulse with τ = 25 - 55ns, typically FWHM = 30 ns
Φ = 6 x 10^9 Wcm^{-2}

(Harilal et al. 2010 APL 96, 111503)

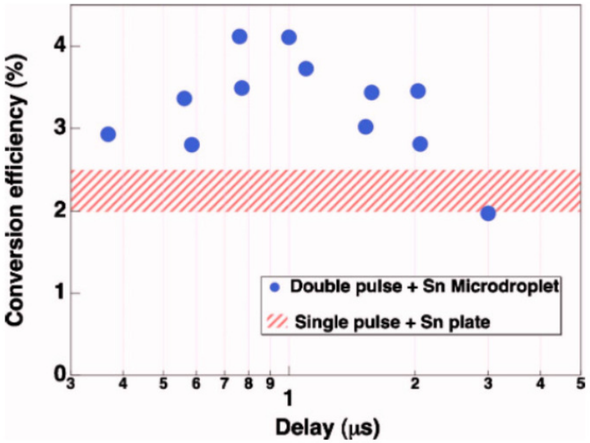


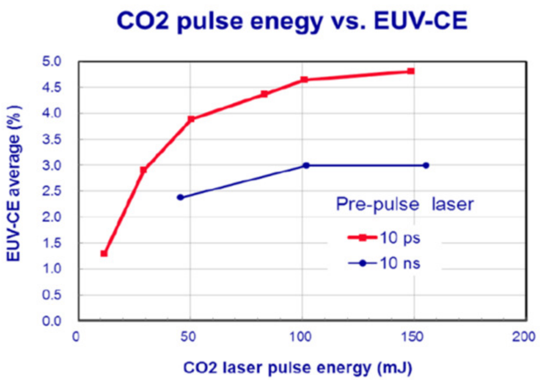
In–Band CE with Droplet Targets

Droplet Targets



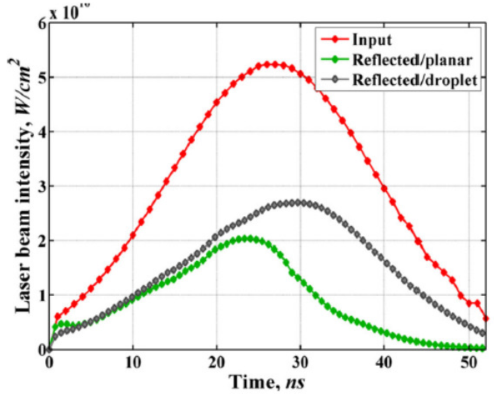
CE vs Φ for single (dashed) and double (solid) pulse irradiation by a 5x10^8 Wcm^{-2} Nd:YAG pre-pulse and 10 ns CO_2 pulse.
Interpulse delay = 180 ns.
Droplet diameter = 40 μm.
Density scale length = 200 μm.
(Nishihara et al. 2008 Phys. Plasmas 15, 056708)





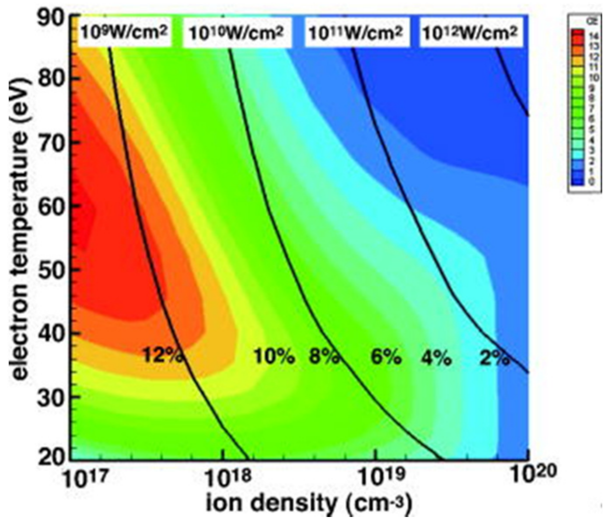
Shortening prepulse gives CE ~5%
Mizoguchi Proc.2016 International Workshop on EUV Lithography
http://www.euvlitho.com/2016/2016%20EUVL%20Workshop%20Proceedings.pdf

Experiment obtained CE = 4%
*Fujioka et al. 2008 Plasma and Fusion Research **4**, 048)*



Reflection from solid surfaces a major problem for CO_2 pulses *(Sizyuk and Hassanein 2012 JAP, 112, 033102)*

Optimised In-Band CE



(Nishihara et al 2008 Phys. Plasmas 15, 056708)

Maximum CE in a mass limited droplet ~6-7% allowing for -10 excitation emission cycles/ion.

If kinetic losses are supressed, CE ~20% at 25≤T_e≤32 eV.
CE values of 11.5% under optimised conditions
(Basko (2016) Phys. Plasmas 23, 083114)

To optimise CE :

- Minimise kinetic losses → low target density
- Minimise opacity effects → ion density <10^{18} Wcm^{-2}
- Mist or vapour target → dual pulse irradiation
- Laser wavelength should be long to optimise laser plasma coupling → CO_2 laser
- Low density implies large plasma scale length and gentle gradients → reflection losses reduced

Colliding Plasma Target

Outline

- Properties of Laser Produced Plasmas
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Colliding plasmas

When two plasmas collide one observes:

1. Interpenetration - counter streaming plasmas pass through each other

2. Stagnation - plasmas collide but do not inter-penetrate and form a 'stagnation layer'. Here the local density and temperature rise rapidly.

Could a plasma stagnation layer provide a suitable target for an EUV or BEUV source?

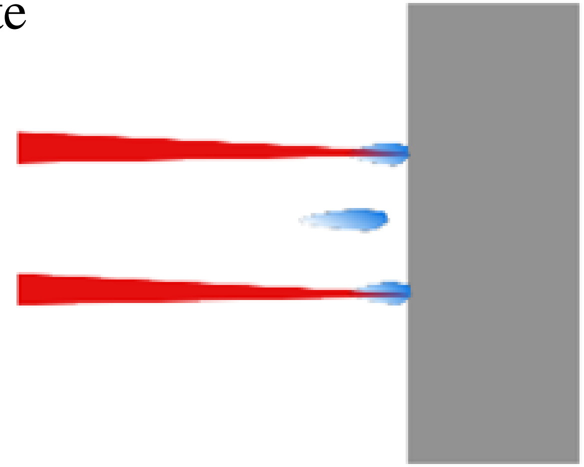
If $n_e \sim 10^{19}$ cm^{-3} and the stagnation layer persisted for an interaction time matched to CO_2 pulse duration perhaps a high CE could be attained.

Collisionality parameter

Collisionality (ζ) is determined by both the mean free path (λ_{ii}) and colliding plasma separation (D).

$$\zeta = D/\lambda_{ii}$$

Large ς, interpenetrate,
Small ς, stagnate

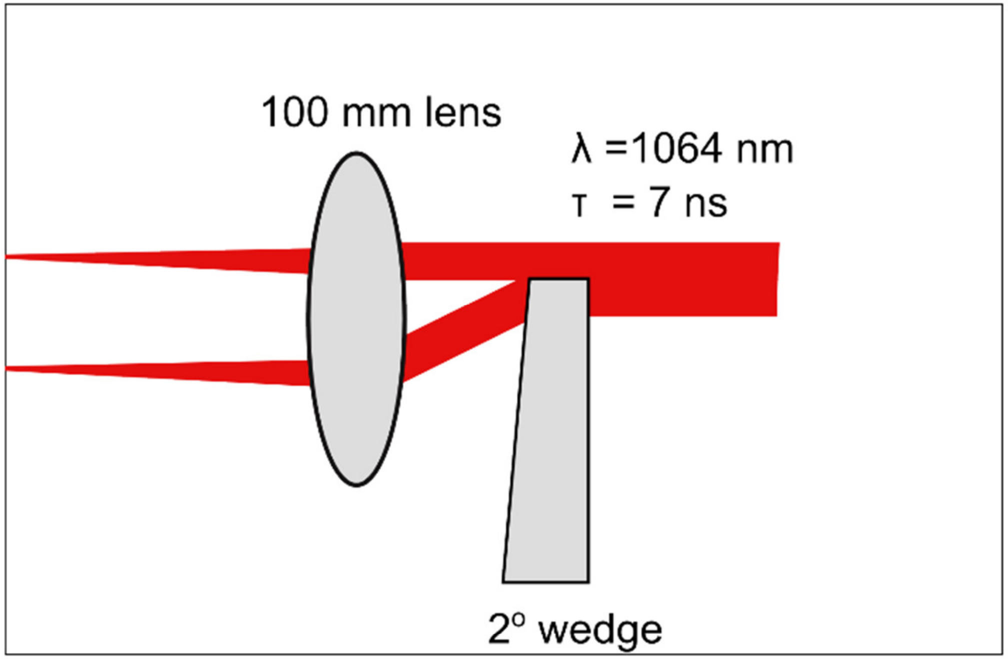


$$\lambda_{ii} = \frac{m_i^2 v_{12}^4}{4\pi e^4 Z^4 n_i ln\Lambda_{12}}$$

- v is the ion velocity - laser power density
- Z is the average ionisation - laser power density
- n_i is the ion density
- Λ_{12} Coulomb logarithm – 10 to 30 for lab plasmas

We can influence the collisionality parameter by changing the distance between the seed plasmas or the laser power density to each seed. it should be possible to tune the plasma density and temperature to make an efficient target.

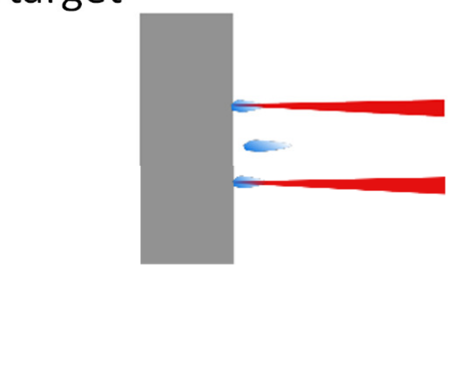
Colliding plasma experiments



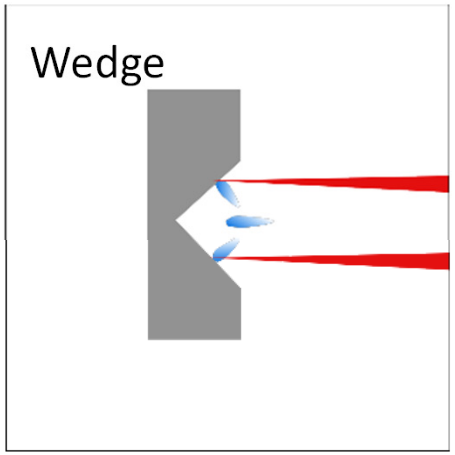
(a)

2 geometries studied

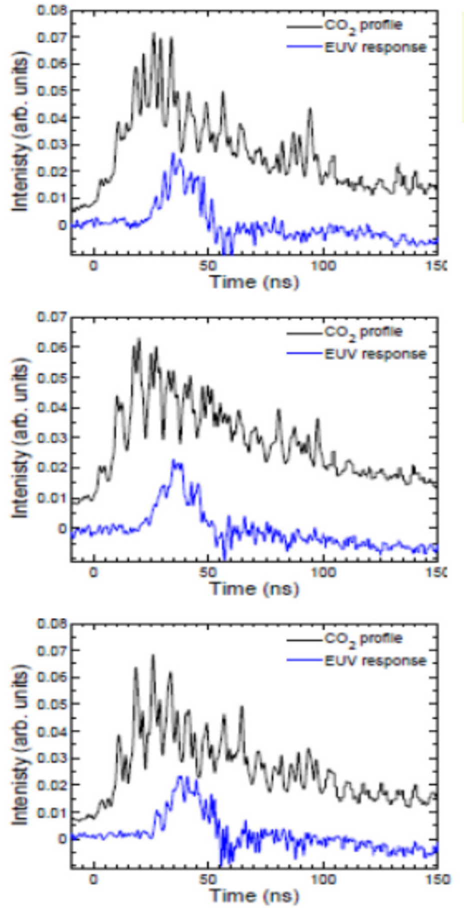
Flat target



(b)



(c)

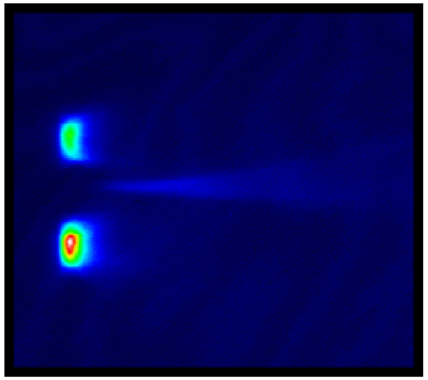


CO_2 pulse shape is irregular.
No EUV emission during 'long' tail.

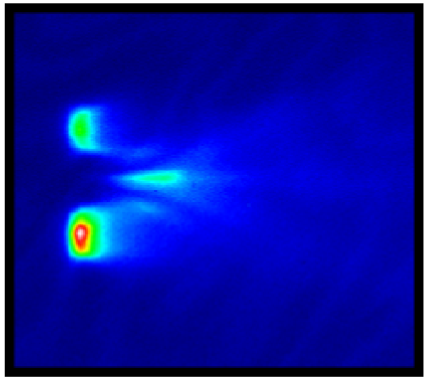
Flat target colliding plasma

Visible imaging

Nd:YAG colliding plasma



Nd:YAG colliding plasma + CO_2 reheat



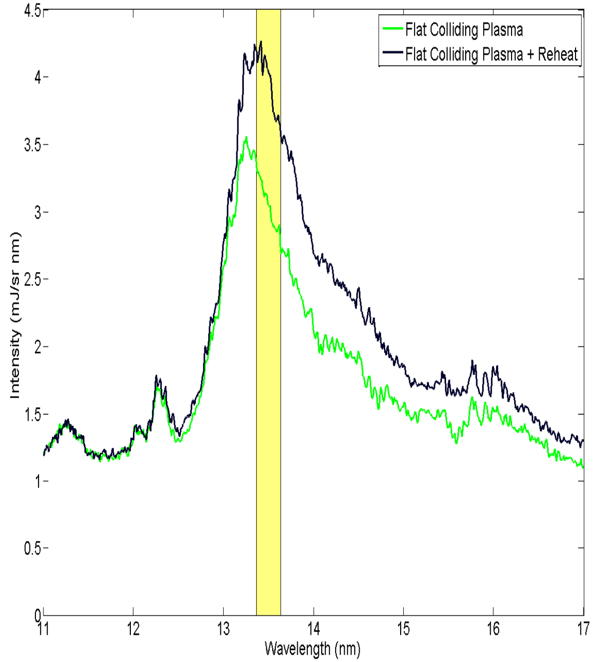
1.4 mm

Imaging system sensitive to light in 400 – 500 nm range.

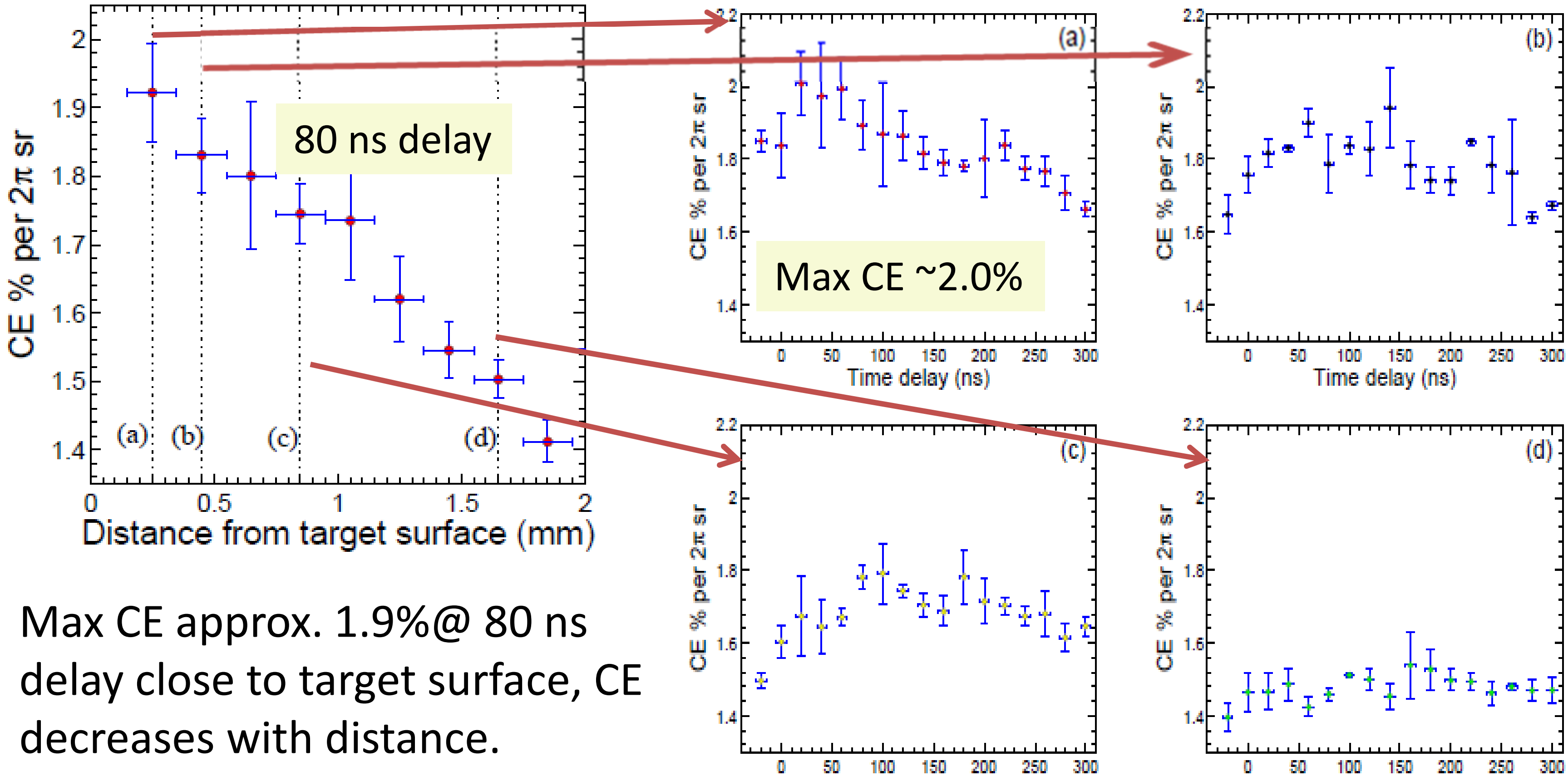
•Highest ion stages emitted along target normal
•Highest ion KE is along target normal ($v_{normal} \sim 10\ v_{lateral}$)
$\leftrightarrow$ λ_{ii} is ~ 100 times greater and $\zeta \sim 100$ times less

Sharply defined stagnation layer

Flat CP and reheat spectra

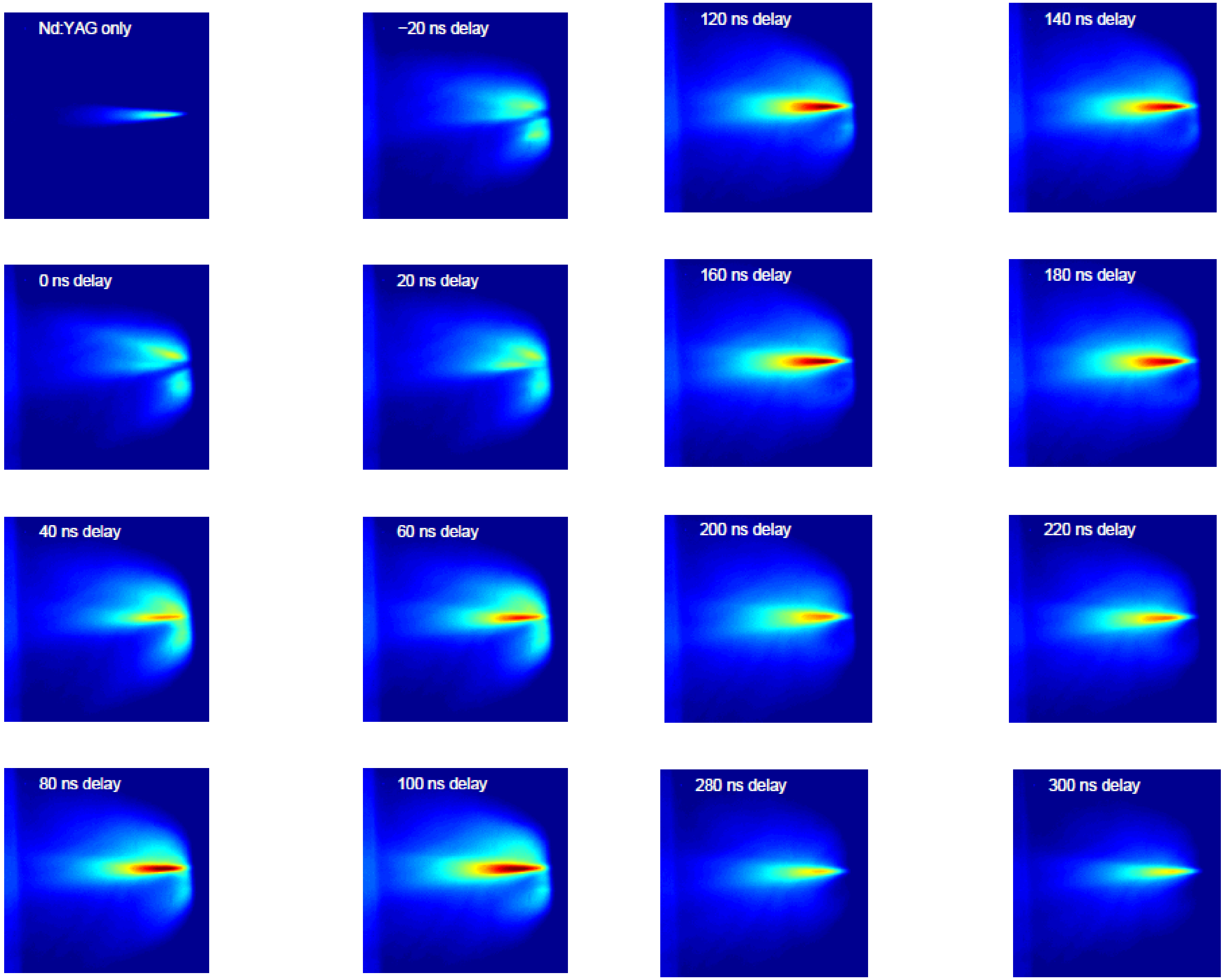


Conversion efficiency



Max CE approx. 1.9%@ 80 ns delay close to target surface, CE decreases with distance.
Also max CE at increasing distances generally reached at later times

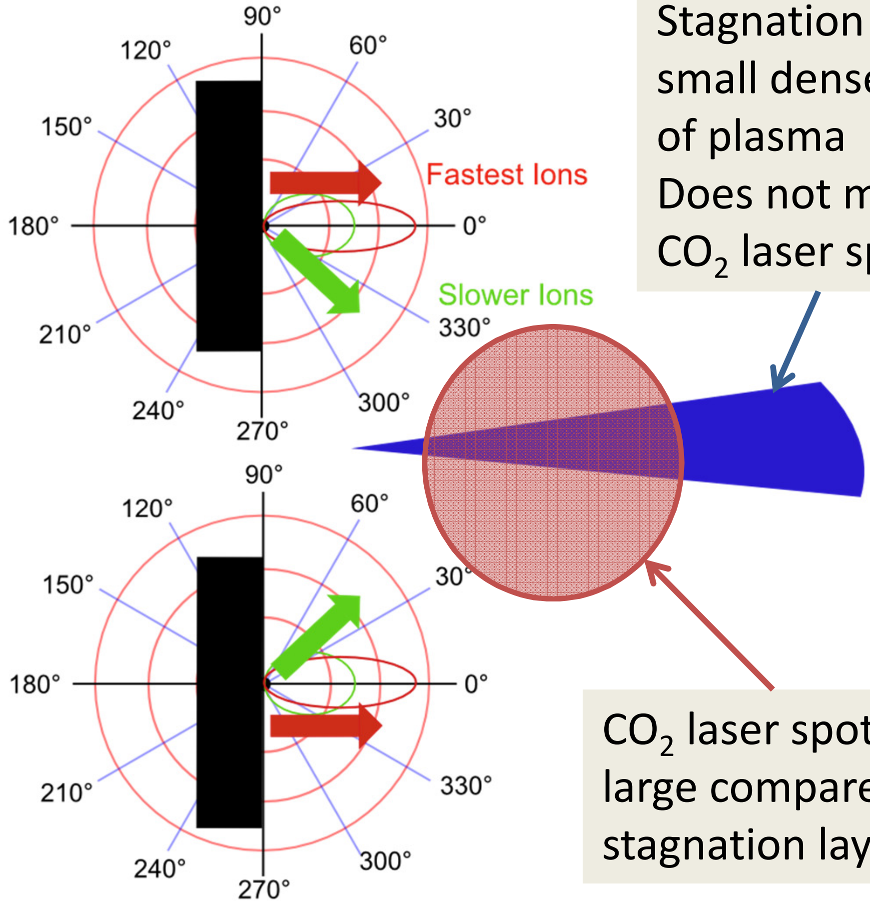
Reheated plasmas for different interpulse delays.



Nd:YAG prepulse
CO_2 main pulse

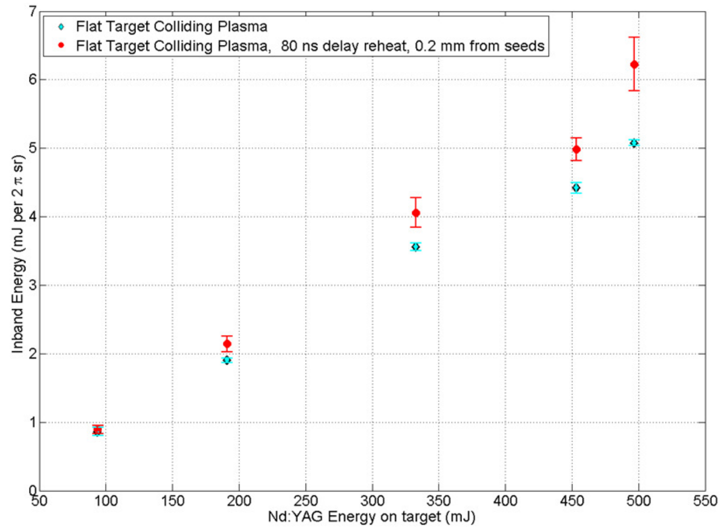
Note that stagnation layer persists for > 300 ns.

Why low efficiency?



Stagnation layer = small dense sheet of plasma
Does not match the CO_2 laser spot size

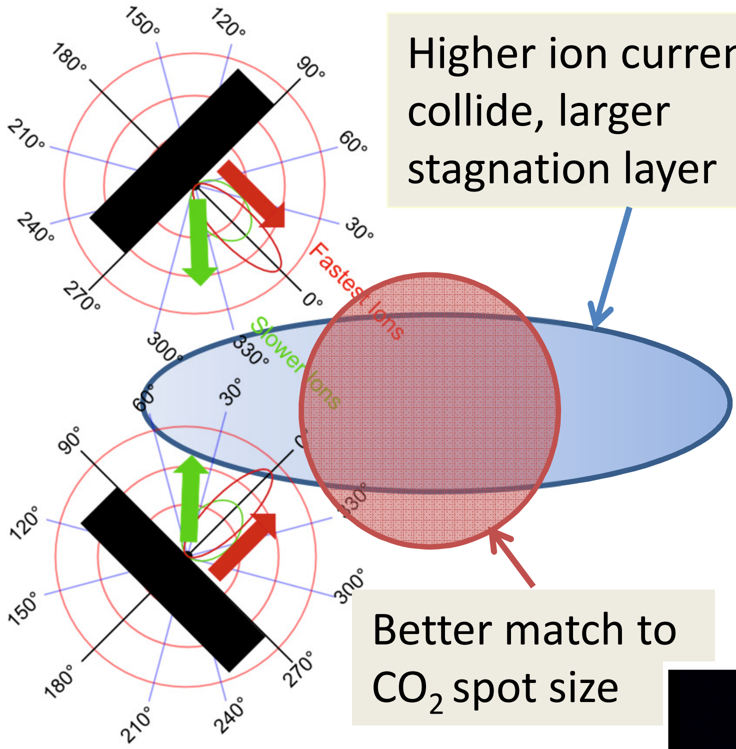
CO_2 laser spot is too large compared to stagnation layer



As Nd:YAG energy increases –
Larger stagnation layer better matched to CO_2 pulse

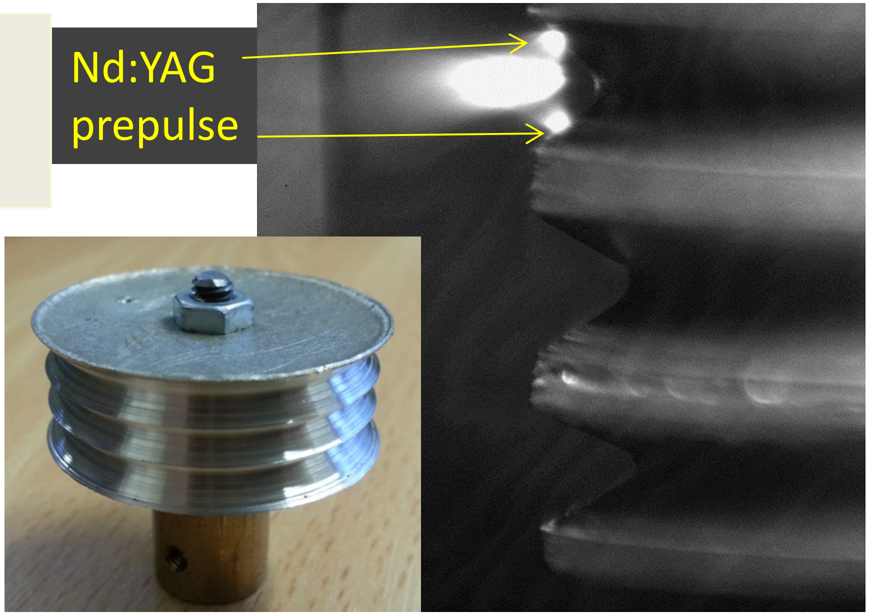
To make a bigger stagnation layer – need more material and more interpenetration

Wedge target

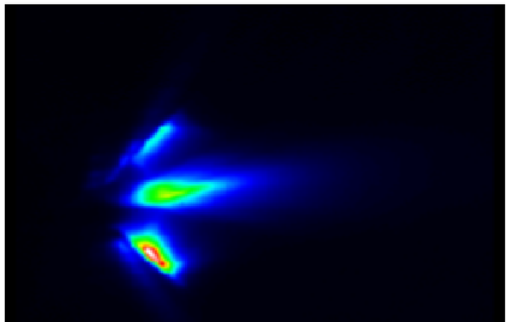


Higher ion currents collide, larger stagnation layer

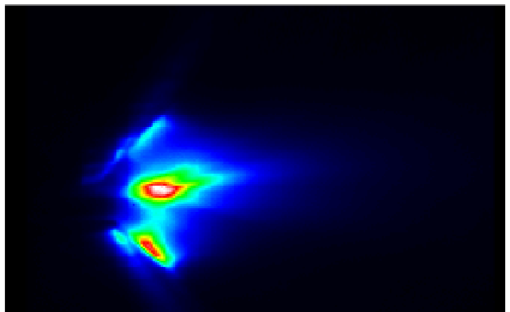
Better match to CO_2 spot size



Visible Imaging system sensitive to λ ~400 – 500 nm

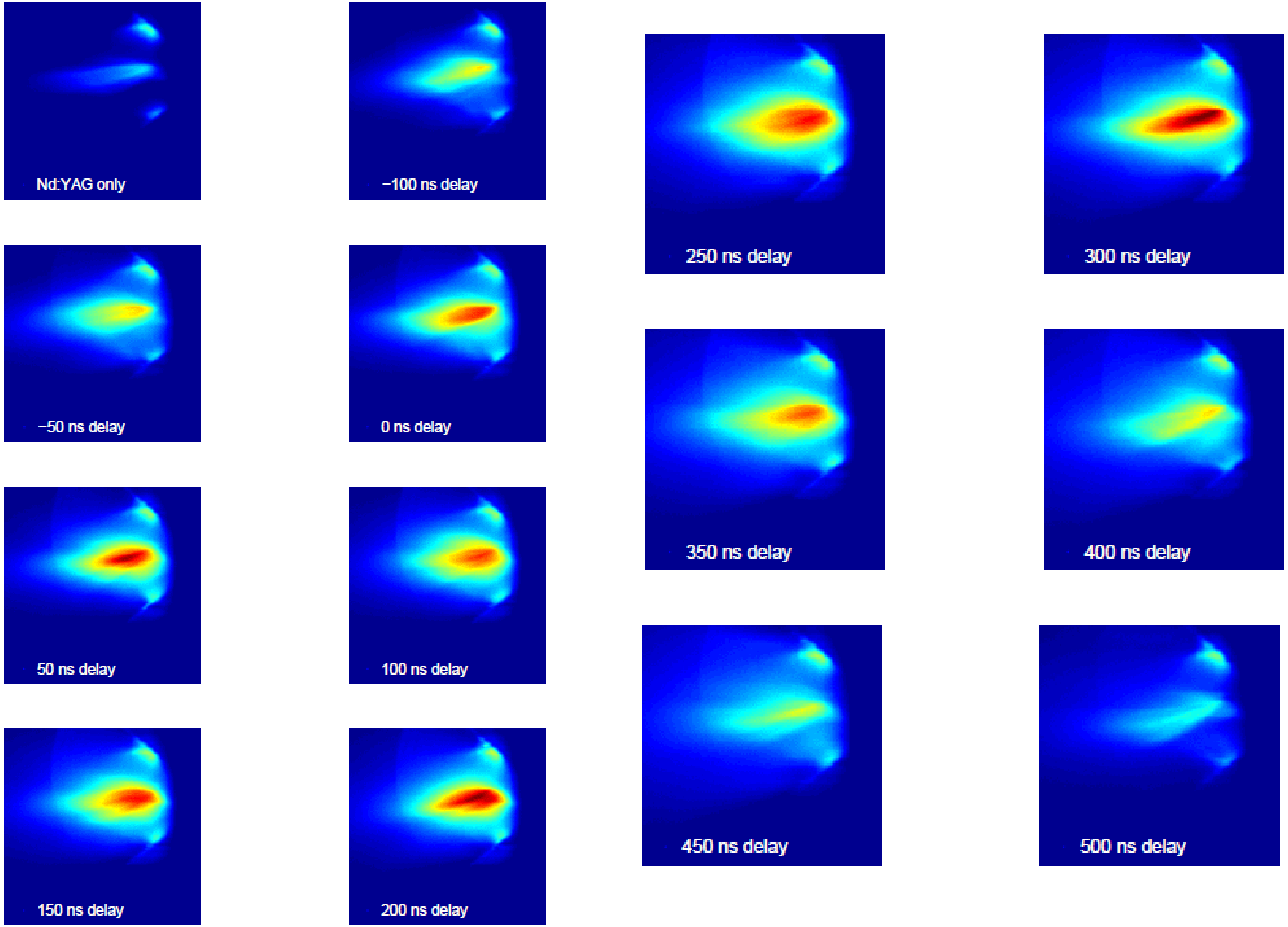


Nd:YAG colliding plasma

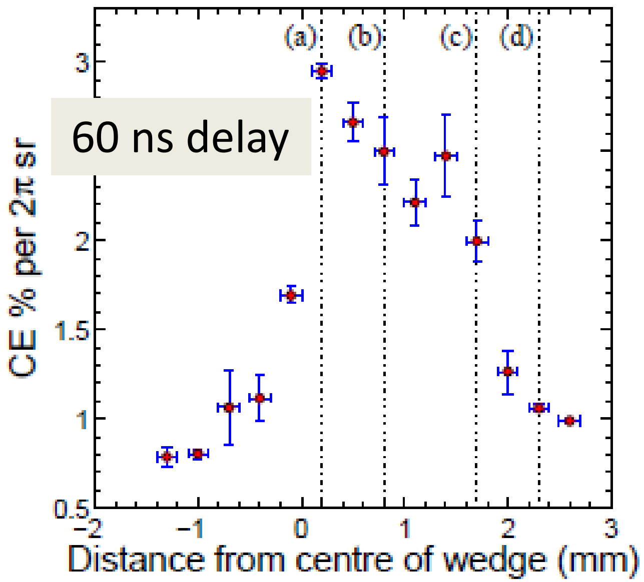


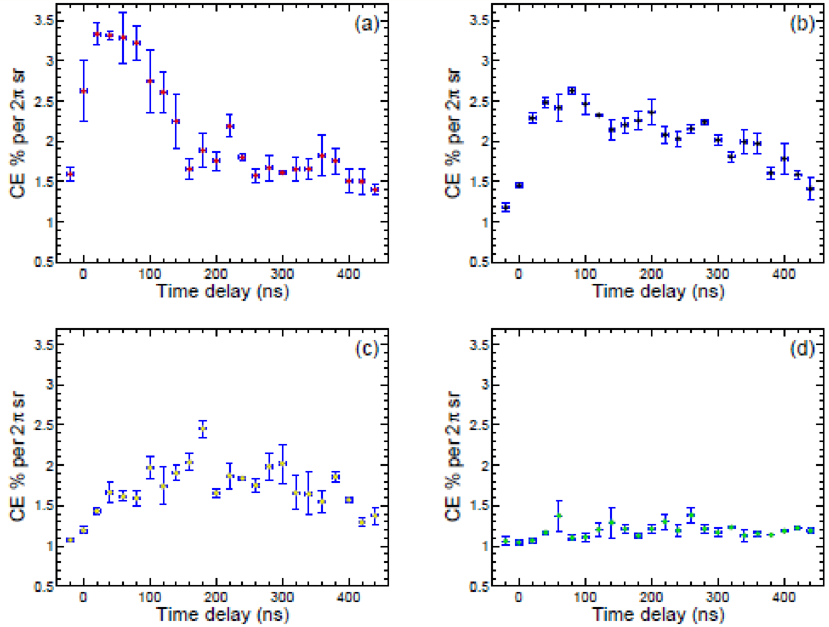
Nd:YAG colliding plasma + CO_2 reheat

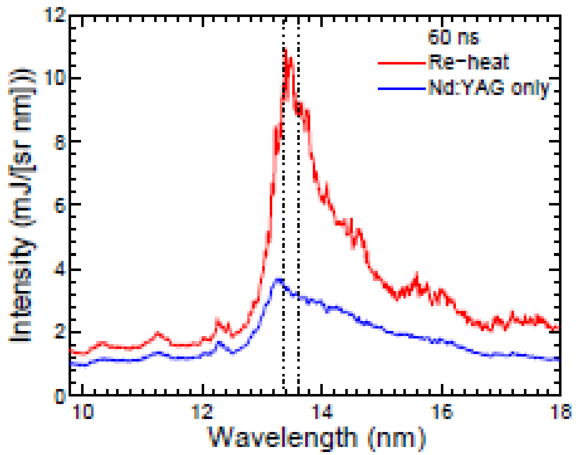
Colliding Plasma Images for different $\Delta\tau$



Reheating along wedge target stagnation layer







Max CE @ 60 ns delay close to wedge centre

Nd:YAG, E~ 135 mJ in each pulse,

$\Phi \sim 1.0\text{x}10^{11}$ Wcm^{-2}

CO_2: E~ 250 mJ, $\Phi = 1.7\text{x}10^{9}$ Wcm^{-2}

CE = 3.3±0.2%

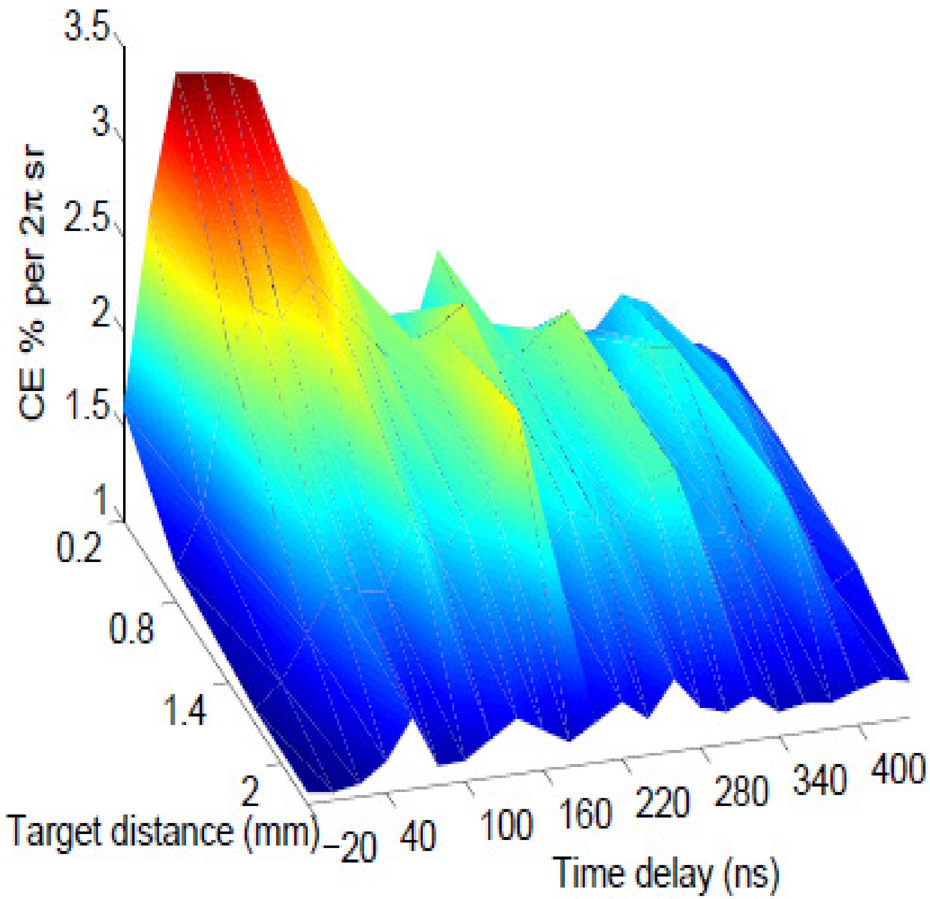
For CO_2 only, CE = 5.1±0.10%

Allowing for overfilling of plasma by

CO_2 CE approximately 7%

(Cummins, et al. 2013 APL 105, 044101)

Summary



Wedge target colliding plasma better matched to CO_2

Better control of initial conditions could give even higher CE.

Shows good energy scaling, energy out increases as input energy increases.

Indicates that with optimum control of pre-pulse conditions, CE>5% is possible

Funding

Science Foundation Ireland Principal Investigator Grants SFI-02/IN.1/I99 and 07/IN1/I1771,

Science Foundation Ireland China Ireland Collaboration Fund.

science foundation ireland
fondúireacht eolaíochta éireann

THANK YOU!